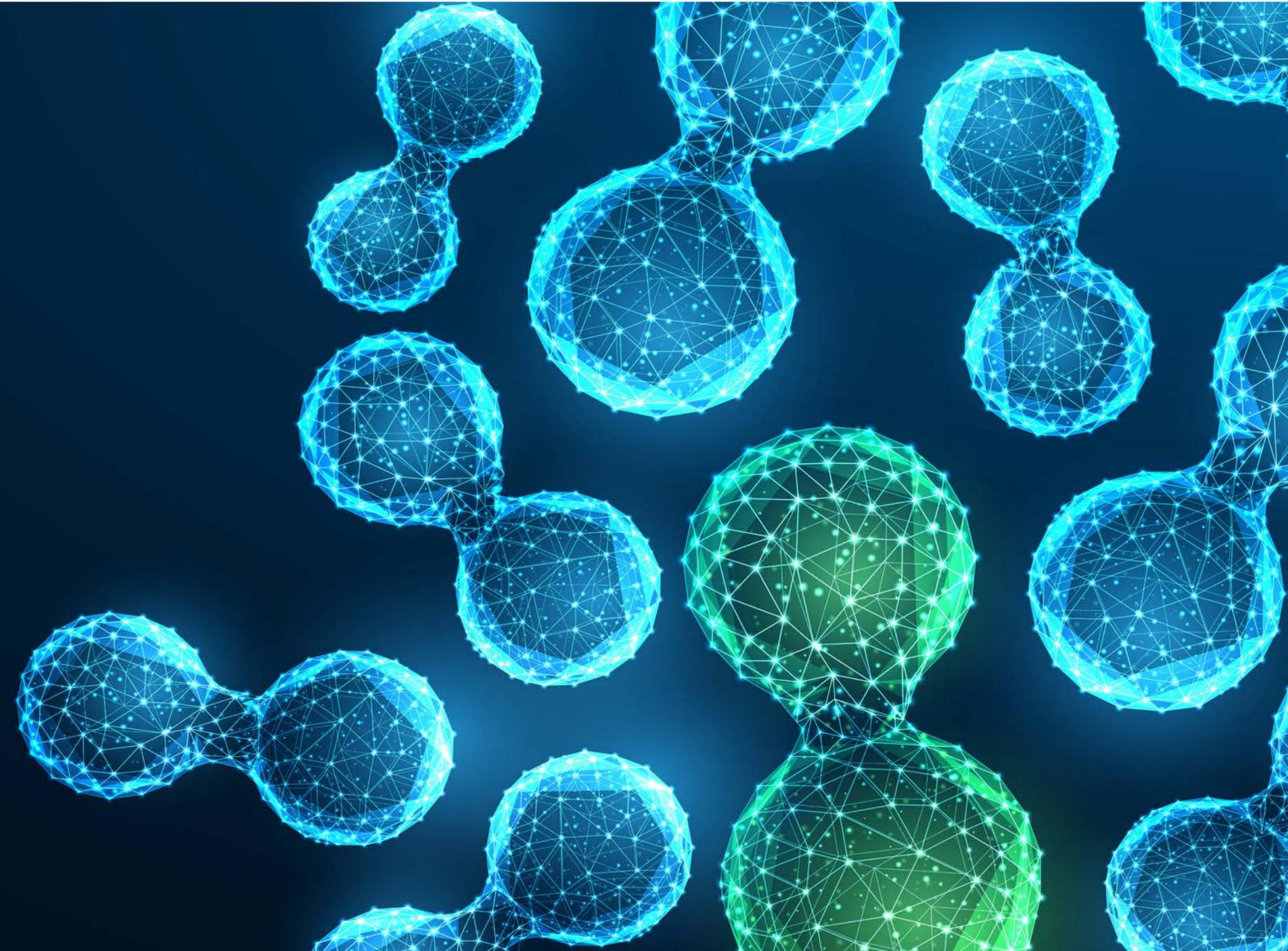
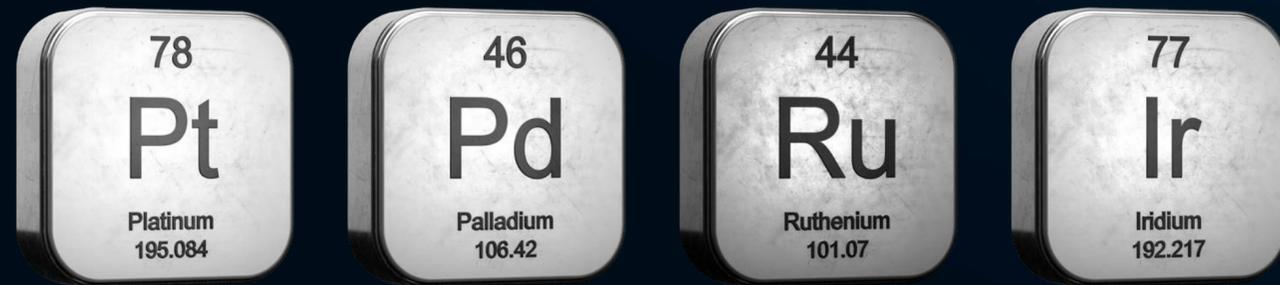


Heraeus

Precious Metals



Debunking Myths: The Role of Platinum Group Metals for a Hydrogen Future

Dr. Jan-Patrick Melchior, Dr. Christian Breuer



Abstract / Introduction

Chapter 1

The Use of Platinum Group Metals in the Hydrogen Economy

Chapter 2

Cost and Efficiency Contribution of Platinum Group Metals in the Hydrogen Sector

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Conclusion

Green hydrogen is widely recognized as a pivotal energy vector allowing for the storage of green electrical energy and for decarbonizing hard-to-abate sectors. New technologies are being developed for production, storage, transport and utilization of green hydrogen. The field has reached a stage where scaled-up production facilities for green hydrogen equipment are already available and a worldwide race to further industrialize the technology is taking place. The push to build up greater capacity for green hydrogen production also involves establishing a mature supply chain. Industry and policy makers see the specific importance of a resilient supply for critical raw materials (CRMs) needed for the hydrogen technologies.

Unfortunately, a variety of misconceptions are repeatedly found in the public discussion on such critical raw materials. In the hydrogen sector, this especially concerns the use of Platinum Group Metals (PGMs). Since policies on critical raw materials are mainly inspired by the battery or solar sectors, existing models are not well suited to the Platinum Group Metals industry. In this white paper the most prevailing myths are addressed and facts on the use and supply of Platinum Group Metals are provided.

Myth 1 Platinum Group Metals are scarce and imply challenges for supply. We should skip the few technologies that need PGMs to increase resilience.

In fact, platinum metals are used in numerous technologies. They are applied at every stage of the hydrogen value chain, not just in “a few expendable technologies.”

Myth 2 Platinum Group Metals are expensive. This strongly contributes to an increase in hydrogen prices.

On the contrary. Platinum metals increase competitiveness and have a positive effect on the price of the end product, hydrogen. They enable operation under harsh conditions and offer high efficiency and durability. As a result, less energy is required for the processing or production of hydrogen. The acquisition costs for platinum metals are recouped through more competitive hydrogen prices. In addition, the raw material costs can be recouped through recycling at the end of the service life. All in all, they make green hydrogen more cost-effective.

Myth 3 The supply of Platinum Group Metals is a challenge for the hydrogen industry in the same way as battery technologies needed to build up Lithium supply or rare earth supply.

Fortunately, the supply of platinum metals for industrial applications is a well-established industry. It does not pose a challenge. Supply chains, production facilities, and expertise in handling the financial and technical aspects of PGMs are well established.

Myth 4 Platinum Group Metals are a uniform group of materials and can be supported or regulated by the same policies.

When viewed correctly, the metals of the platinum group do not form a uniform group. The available quantities and market situation of the individual metals differ considerably. A policy that may be beneficial for one material may prove detrimental to the market for another.

The Use of Platinum Group Metals in the Hydrogen Economy

Chapter 1

Platinum Group Metals (PGMs) are by nature linked to the green hydrogen industry and are irreplaceable in many of its key technologies.

Platinum (Pt), Iridium (Ir), Ruthenium (Ru), Palladium (Pd), Rhodium (Rh), are used in various applications along the chain of production, transport and use of green hydrogen.

Avoiding specific technologies that use PGMs does not mean that they will not play a role in the hydrogen sector.

Platinum Group Metals, in particular the metals platinum (Pt), iridium (Ir), ruthenium (Ru) and palladium (Pd) are used in every step of the green hydrogen lifecycle. In production, processing and multiple end-applications PGMs are used to either

catalyze a reaction, to improve efficiency and reduce electrical losses, or to protect components from degrading under typically harsh operation conditions. Thus, they are key to both efficiency and durability of the equipment used in these applications.

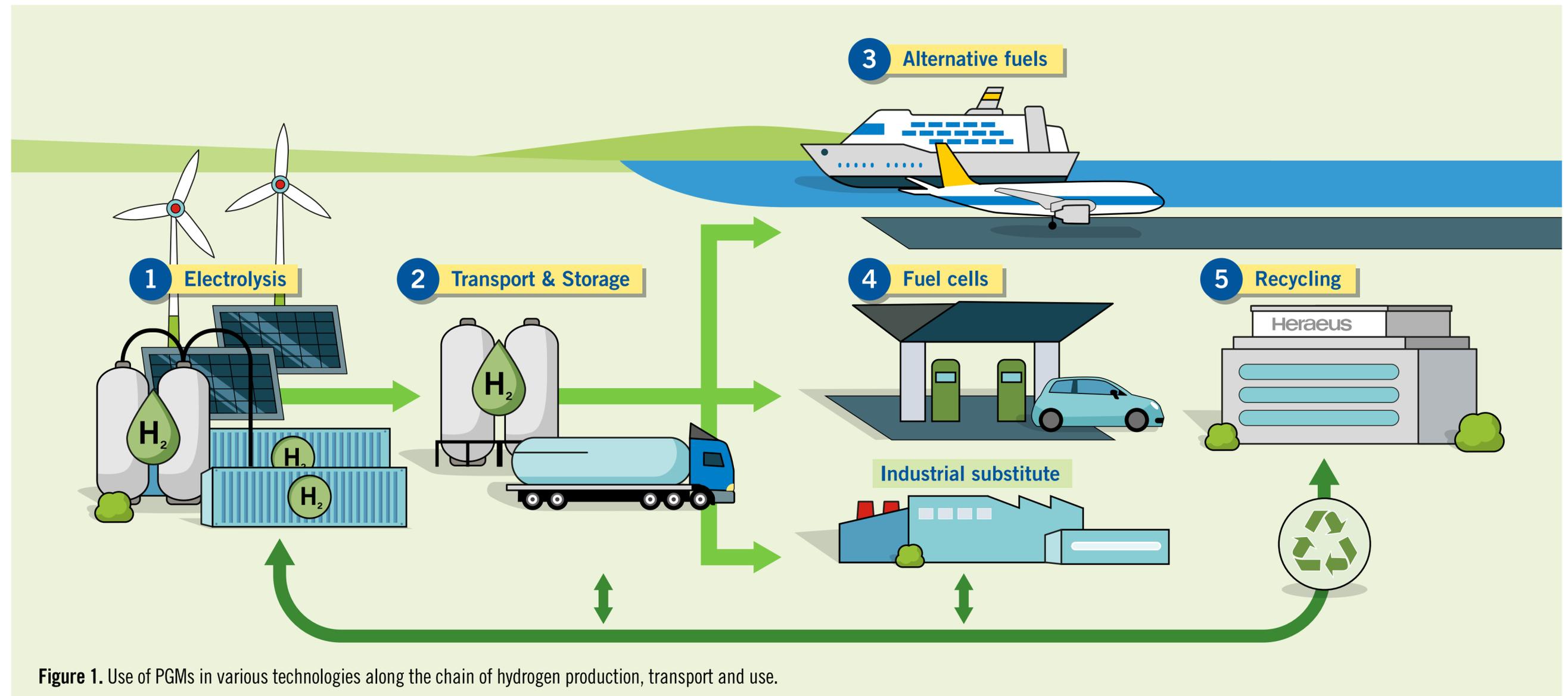


Figure 1. Use of PGMs in various technologies along the chain of hydrogen production, transport and use.

1.1 PGMs in Green Hydrogen Production

Chapter 1

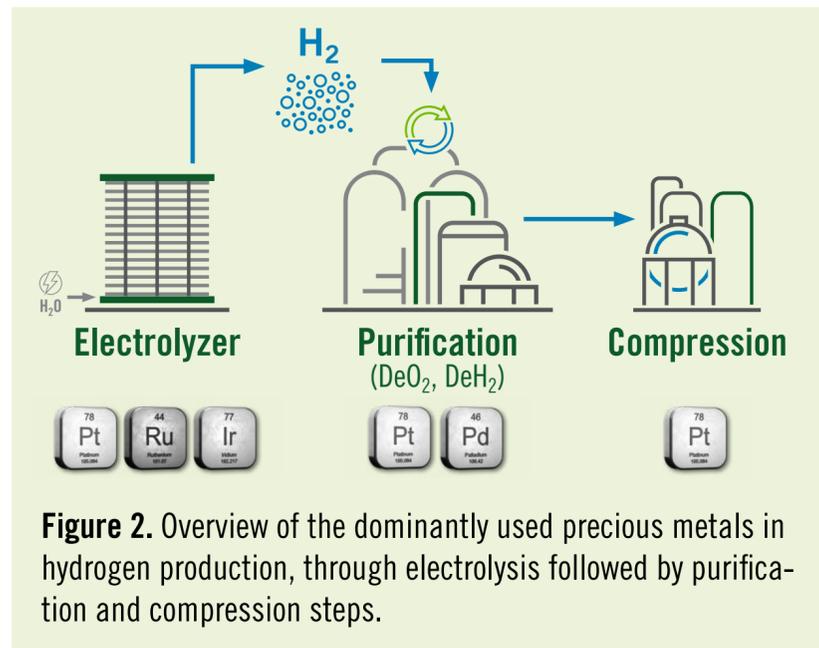
1.1 PGMs in Green Hydrogen Production

1.2 Hydrogen Storage and Transport

1.3 PGMs in Hydrogen Purification

1.4 PGMs in Green Hydrogen Utilization

The production of green hydrogen starts with the generation of hydrogen through electrolysis from water and green electricity. In many cases, though, hydrogen purification and the compression of hydrogen for further transport are needed before hydrogen is shipped or used. In **figure 2** the possible use of PGMs in the respective steps along this processing chain is shown.



For hydrogen production through electrolysis the various water electrolyzer technologies are shown in **figure 3**. For low temperature technologies Platinum Group Metals are a functional part of the electrocatalysts that enable the electrochemical reactions to transform water to hydrogen and oxygen using electricity. Precious metals are also used in protective coatings to ensure the long-term durability of the components.

Of the available electrolyzer types liquid Alkaline Water Electrolyzers (AWE) are installed at the largest overall capacity. Different subtypes of such low temperature systems exist, which can apply non-PGM electrocatalysts. However, more efficient and durable systems employ so-called Advanced Alkaline Electrodes, utilizing ruthenium or iridium electrocatalysts.

For acidic low temperature Proton Exchange Membrane Water Electrolyzers (PEMWE) no feasible options other than PGM electrocatalysts exist that enable significant durability and efficiency. Highly conductive and durable Pt coatings of stack components additionally increase the efficiency.

PEMWE systems are widely seen as the best option for intermittent and renewable energy sources and are the second most installed technology to date.

Novel Anion Exchange Membrane Water Electrolyzers (AEMWE), are often advertised with the option for PGM-free operation. However, it has been shown that non-PGM cathode catalysts do not provide the needed lifetime and cause reduction in achievable current densities by at least a factor of 2 in comparison to PGM-containing catalysts. That means non-PGM AEMWE are generally less efficient than PGM-based alternatives.

Type	AEMWE Anion Exchange Membrane Water Electrolyzer	AWE Liquid Alkaline Water Electrolyzer	PEMWE Proton Exchange Membrane Water Electrolyzer	PCEC Proton Conducting Ceramics Electrolyzer	SOEC Solid Oxide Electrolyzer Cell
Electrocatalyst	Pt, Ru, Ir	Ru, Ir	Pt, Ru, Ir		
Protective coating	Pt		Pt	Pt	Pt
Purification	Pd, Pt	Pd, Pt	Pd, Pt	Pd, Pt	Pd, Pt
Operation temperature	60°C	< 50°C	60-80°C	>400°C	>500°C
Industrialization/deployment	Early applications	High	High	Research and Early applications	Intermediate
Typical stack size	2.4 kW – 1 MW	1 MW – 10 MW	0.15 – 6 MW	----	0.15 – 0.5 MW

Figure 3. Electrolyzer types and the specific precious metals used as either electrocatalyst in the hydrogen production, protective and conductive coatings, or in subsequent hydrogen purification.

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1.1 PGMs in Green Hydrogen Production

1.2 Hydrogen Storage and Transport

1.3 PGMs in Hydrogen Purification

1.4 PGMs in Green Hydrogen Utilization

Green hydrogen can either be stored and transported in compressed or liquid form, or as part of other “green molecules”. As shown in **figure 4** hydrogen can be the basis for classical synthesis routes for ammonia (NH₃), methane (CH₄), or methanol (MeOH). Efficient synthesis is supported by catalysts employing, for example, ruthenium. For hydrogen storage and transport liquid organic hydrogen carriers (LOHC) can be “loaded” with hydrogen through a hydrogenation process that employs platinum-, palladium-, or ruthenium-based catalysts.

Dehydrogenation, i.e., the recovery of hydrogen from the “hydrogen loaded” LOHC is catalyzed mainly using palladium- and platinum-containing catalysts. While the hydrogen derivatives ammonia (NH₃), methane (CH₄), or methanol (MeOH) can be used as raw materials in the chemical industry, hydrogen can also be recovered from them. Different types, e.g., of ruthenium-based catalysts can be used in the cracking of ammonia to form hydrogen and nitrogen.¹ The release of hydrogen from methane dominantly is done via steam methane reforming (SMR). This process commonly uses base metals such as nickel, yet may require rhodium, ruthenium or platinum reformer catalysts. Resulting from SMR is a mixture of hydrogen, CO₂ and CO, which can

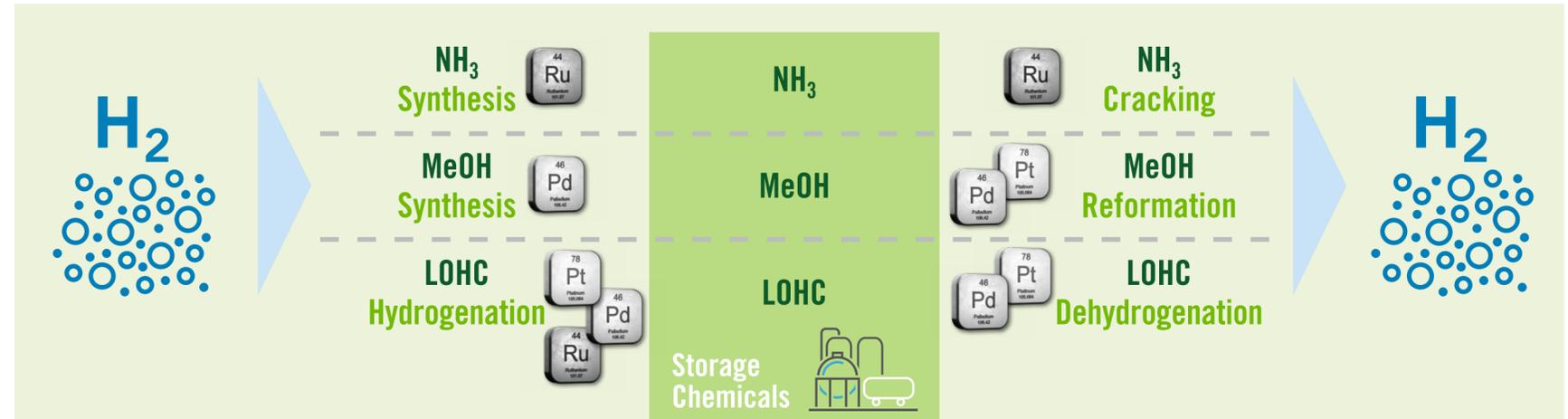


Figure 4. Overview of the dominantly used precious metals in hydrogen storage and transportation by conversion to and from NH₃, MeOH, and LOHC.

serve as an important raw material for synthesis in the chemical industry, or as basis to gain pure hydrogen through further purification. To regain hydrogen from methanol, the required reforming step can equally benefit using palladium- or platinum-containing catalyst in comparison to alternative non-PGM catalysts.

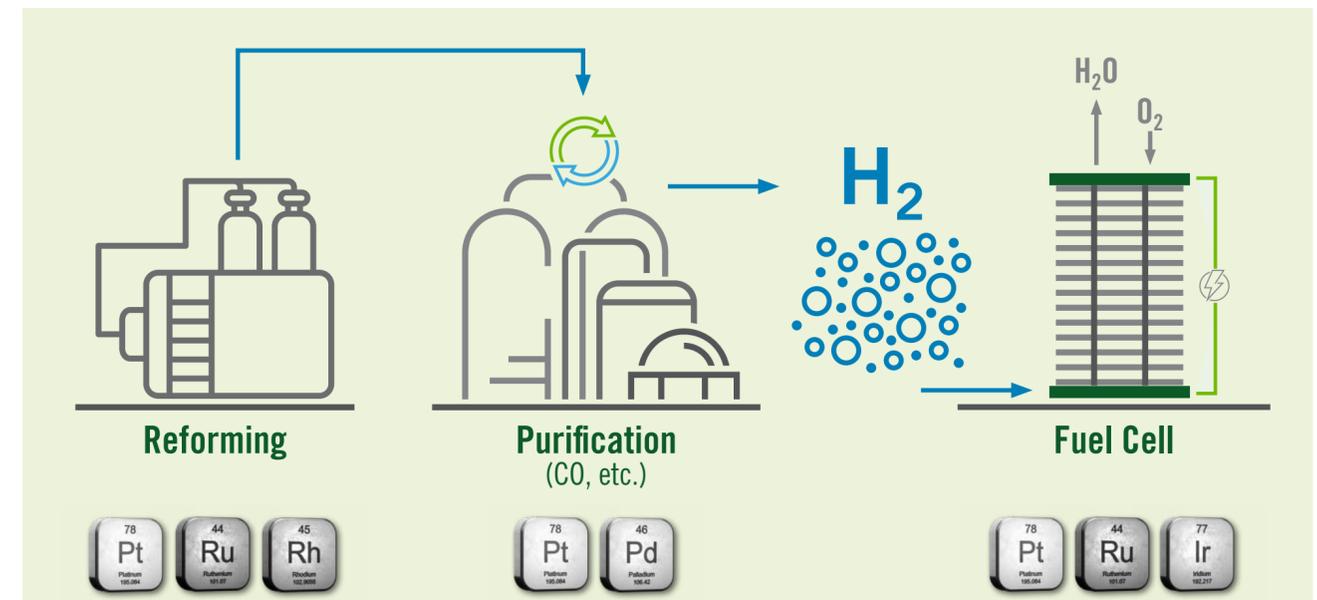


Figure 5. Overview of the dominantly used precious metals in the reconversion of hydrogen or hydrogen derivatives (NH₃, MeOH) to electrical energy. Depending on the type of fuel cell, reconversion can be directly from derivatives or following reforming and purification of the derivatives to pure hydrogen.

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1.1 PGMs in Green Hydrogen Production

1.2 Hydrogen Storage and Transport

1.3 PGMs in Hydrogen Purification

1.4 PGMs in Green Hydrogen Utilization

Whether hydrogen is produced directly from green energy by electrolysis, recovered from green molecules or produced from grey molecules through reforming, pyrolysis, or gasification: purification based on its end-use is needed. This usually entails a multi-stage purification process to achieve the required level of purity. **Figure 6** provides a non-exhaustive overview of a variety of purification technologies. The decisive factors to choose a purification technology are the types of impurities, the levels of contamination, the gas pressure, the flow rates, and finally the purity targets.

Hydrogen from electrolysis almost always contains oxygen and, especially in high temperature electrolysis, water vapor. In combination with drying processes – used in so-called deOxo-dryers – precious metal catalysts, i.e. based on platinum and/or palladium, are unrivalled in terms of efficiency and long-term stability for the conversion and removal of oxygen.

Hydrogen produced from natural gas or other hydrocarbons needs more involved purification steps, as more impurities, e.g., carbon monoxide, carbon dioxide, and water need to be removed. Purification methods can include gas scrubbing, cryogenic distillation or pressure swing adsorption which work without Platinum Group Metals. However, catalytic methods such as the water-gas shift reaction (WGS) – converting carbon monoxide and water into carbon dioxide and hydrogen

Type	Catalytic DeOxygenation	Catalytic Water-Gas-Shift & Polishing	Palladium-Membranes	Electrochemical Purification / Compression	(Pressure Swing) Absorption	Gas Scrubbing	Cryogenic Distillation
Hydrogen Source	Electrolyzer	Reformer	Diverse	Diverse	Diverse	Diverse	Diverse
Main Target Impurities	Oxygen	CO, H ₂ O, ...	CO ₂ , N ₂ , CH ₄ , NH ₃ , H ₂ O, ...	CO ₂ , CO, N ₂ , O ₂ , CH ₄ , H ₂ O, ...	CO ₂ , CH ₄ , H ₂ O, ...	CO ₂ , ...	CO ₂ , CH ₄ , H ₂ O, ...
Catalysts / PGM Active Materials							
Scale / Flow Rates (Common)	Small/Medium/High	Small/Medium/High	Small/Medium	Small/Medium/High	Medium/High	Medium/High	Medium/High

Figure 6. Different hydrogen purification technologies and the Platinum Group Metals used therein. (exemplary)

– can benefit from the use of platinum catalysts. Further, trace carbon monoxide removal via preferential oxidation (PROX) or methanation gains from the use of platinum- or ruthenium-based catalysts.

For reforming, water-gas-shift and polishing, precious metal-containing systems demonstrate their advantages, particularly in decentralized applications, where they allow for lower operating temperatures, higher yields, and more stable operation in the presence of some contaminants. Novel palladium membranes provide one of the most effective methods of hydrogen purification in decentralized applications with the added advantage of operating at higher pressure.



1.4 PGMs in Green Hydrogen Utilization

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1.1 PGMs in Green Hydrogen Production

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1.3 PGMs in Hydrogen Purification

1.4 PGMs in Green Hydrogen Utilization

Finally, green hydrogen and its derivatives can be used for the generation of electrical power. One of the most efficient ways to generate electricity is via the use of fuel cells. These convert fuels and oxygen into water and energy directly through an electrochemical reaction.

The number of mature fuel cell technologies is much larger than the number of mature electrolyzer technologies (see figure 7) and differences in the use cases for fuel cells are also much broader than that of electrolyzers. Each technology offers specific advantages and

disadvantages for the various use cases – broadly classified as stationary, transport, and portable (see figure 8). Possible variations in the requirements for use cases include the size of the system, tolerated variations in operational conditions (temperature, pressure, etc.), feed gases (hydrogen, hydrocarbons, nitrogen-hydrogen compounds) and the tolerated fuel impurities.

A common theme among the different fuel cells is that without the use of PGMs they either do not work at all, or at least not efficiently or not durable enough. At operation temperatures below 400°C PGM electro-

catalysts are indispensable and at higher temperatures the use of PGM catalysts in the Balance-of-Plant (BoP) are mandatory to ensure a stable operation.

The Proton Exchange Membrane Fuel Cell (PEMFC) technology dominates the fuel cell sector, in overall production amounts and in the number of use cases. The technology has seen most investments in research and industrialization for its role in transportation. The technology has therefore also seen the most significant technological diversification that includes the use of different PGM electrocatalysts for different use cases.

Type	AEMFC Anion Exchange Membrane	AFC Alkaline Fuel Cell	DMFC Direct Methanol Fuel Cell	PEMFC Proton Exchange Membrane Fuel Cell	PAFC Phosphoric Acid Fuel Cell	HT-PEMFC High Temperature – Polymer Electrolyte Fuel Cell	RMFC Reformer Methanol Fuel Cell	PCFC Protonic Ceramics Fuel Cell	MCFC Molten Carbonate Fuel Cell	SOFC Solid Oxide Fuel Cell
Electrocatalyst										
Protective coating										
Reformer, etc.										
Operation temperature	< 60°C	< 80°C	70 – 90°C	60 – 120°C	150 – 220°C	160 – 200°C		> 400°C	> 600°C	> 500°C
Fuel	Hydrogen (high purity, NH ₃ tolerant)	Hydrogen (high purity, NH ₃ tolerant), N ₂ H ₄	Methanol (high purity)	Hydrogen (high purity)	Hydrogen (low purity)	Hydrogen (low purity)	Methanol (industrial)	Hydrogen (low purity), Ammonia	Hydrocarbons, Hydrogen	Hydrocarbons, Ammonia, Hydrogen
Industrialization / deployment	Research, Early application	High	High	High	High	Low	Low	Research, Early application	Low	Intermediate
Typical stack size	--	1 – 100 kW	0.04 – 50 kW	80 – 300 kW	5 – 400 kW	0.5 – 100 kW		--	300 kW	1 kW – 10 MW

Figure 7. Fuel cell types and the specific precious metals used as either electrocatalysts, protective and conductive coatings, or as part of a potential reforming step.

Chapter 1

1.1 PGMs in Green Hydrogen Production

1.2 Hydrogen Storage and Transport

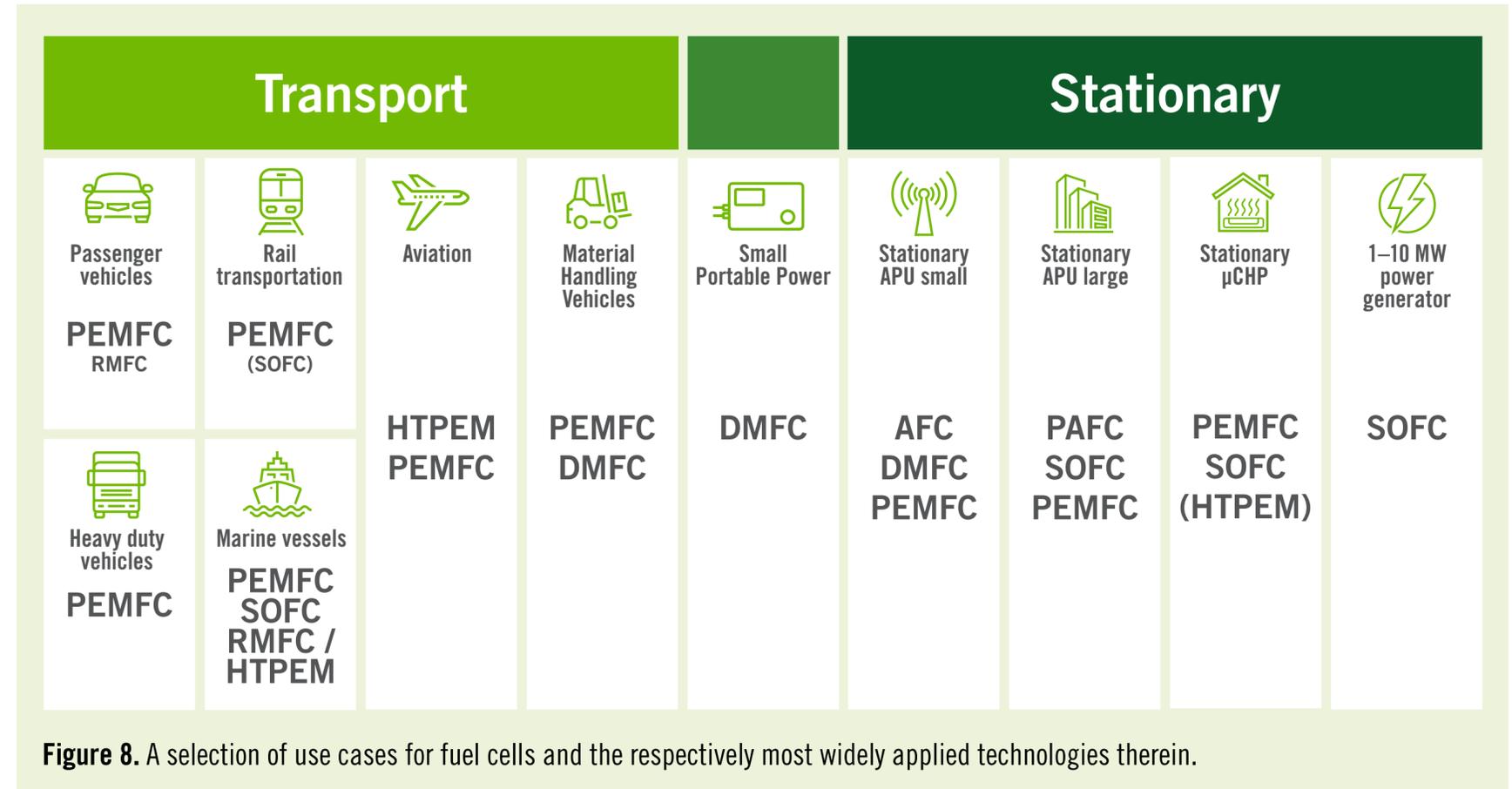
1.3 PGMs in Hydrogen Purification

1.4 PGMs in Green Hydrogen Utilization

The standard electrocatalyst materials for high purity feed streams in transport applications of fuel cells as defined by ISO 14687 are platinum or platinum alloy-based. For especially demanding use cases iridium-based catalysts can be added to extend a systems lifetime or its tolerance to a wider range of operational conditions. For hydrogen feed gases with higher impurities, i.e., gas generated through reforming without additional or sufficient purification, ruthenium-containing catalysts are used.

In terms of installed capacities and number of sold devices per year the PEMFC is followed by other mature alternative fuel cell types, that dominate in their respective niche, i.e., Solid Oxid Fuel Cells (SOFC), or Phosphoric Acid Fuel Cell (PAFC), for large stationary applications, Alkaline Fuel Cells (AFC) for smaller stationary applications and Direct Methanol Fuel Cells (DMFC) for mobile applications.

High temperature fuel cells, like Proton Conducting Ceramic Fuel Cells (PCFC), Molten Carbonated Fuel Cells (MCFC) and Solid Oxid Fuel Cells (SOFC) work without PGM electrocatalysts. Those technologies can also be operated directly with hydrocarbons like methane, but efficient rhodium- or ruthenium-based reformer or pre-reformer catalysts improve the efficiency and can be mandatory for a stable operation.



Alkaline fuel cells like the liquid Alkaline Fuel Cell (AFC) and the Anion Exchange Membrane Fuel Cell (AEMFC) face the same issues as the alkaline electrolyzer, i.e., operation without PGMs is possible but suffers from often unacceptable decrease in lifetime and efficiency in comparison to the use of PGM electrocatalysts.

Acidic intermediate and low temperature fuel cells depend on the use of PGM electrocatalysts. This

group includes the Phosphoric Acid Fuel Cell (PAFC), its derivative the phosphoric acid containing High Temperature - Polymer Electrolyte Membrane Fuel Cell (HT-PEMFC), the Proton Exchange Membrane Fuel Cell (PEMFC) and its derivative the methanol fed Direct Methanol Fuel Cell (DMFC). The acidic nature of the operation conditions also necessitates non-corrosive but still electrically conductive coatings, which have historically also been achieved by using PGMs or, alternatively, the precious metal gold (Au).

Cost and Efficiency Contribution of Platinum Group Metals in the Hydrogen Sector

Chapter 2

Although PGMs are scarce and expensive their net-effect on the total cost of ownership is positive, not negative.

The higher capex that is initially needed is much smaller than the impact of the higher efficiency and increased lifetime.

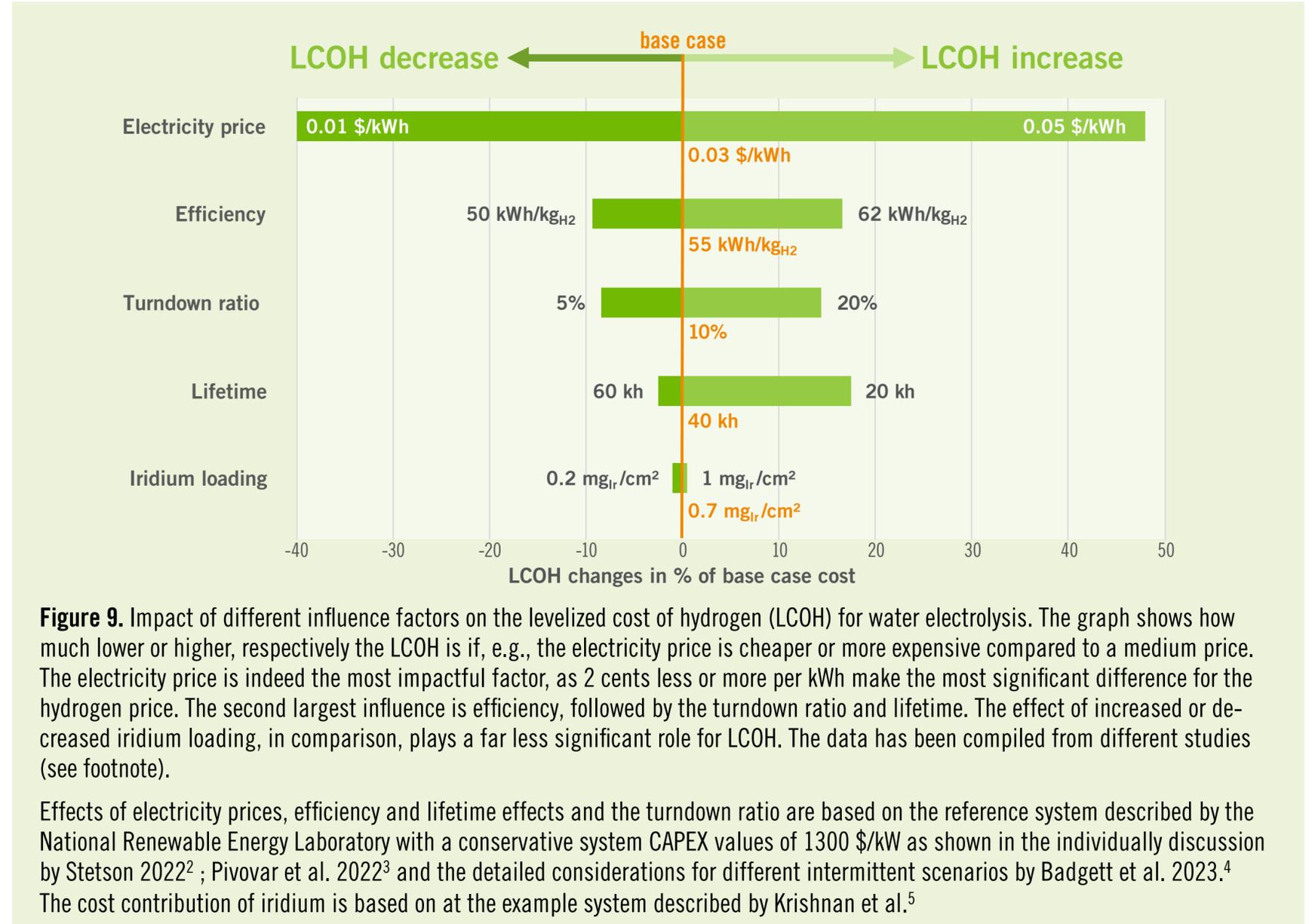
The public and political discussion on green hydrogen production often singles out the use of critical raw materials in electrolyzers or other hydrogen related applications and the relatively high prices of Platinum Group Metals. However, this argument is misleading: While it is true that the initial material costs for a precious metal catalyst are higher than for a non-precious metal catalyst, this is not the most relevant aspect. For applications that run a long time, the efficiency of the process as well as the durability of the component has a much higher financial impact than the initial investment costs.

Commercial considerations for using PGMs in PEM water electrolyzers

The leading factor for the economic viability of an electrolyzer project are its associated levelized costs of hydrogen (LCOH). LCOH broadly describe the cost to produce a kilogram of hydrogen considering the overall production amount and accumulated costs to install, maintain and operate the electrolyzer during its full lifetime. Those costs are not dominated by the capital expenditure to install the electrolyzer, but by the costs to operate the equipment. Highly efficient electrolyzers produce more hydrogen from the used electricity and thus reduce the LCOH. This is most pronounced in areas with higher electricity costs. Highly flexible electrolyzers can operate at different load points, operate up to lower loads, switch on and off quickly, and increase the average hours of opera-

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https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review22/plenary6_stetson_2022_o-pdf.pdf?sfvrsn=8d571d06_0

3 B. Pivovar, M. Ruth, R. Ahluwalia; (2022, June 6) H2NEW: Hydrogen (H2) from Next-generation Electrolyzers of Water LTE Task 3c: System and Technoeconomic Analysis; 2022 Annual Merit Review and Peer Evaluation Meeting, Washington, DC

4 A. Badgett, J. Brauch, P. Saha, and B. Pivovar (2023) Adv. Sustainable Syst. 2300091

5 S. Krishnan, V. Koning, M.T. de Groot, A. de Groot, P. Granados Mendoza, M. Junginger, G.J. Kramer et al., International Journal of Hydrogen Energy, 48(52) 32313-32330

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tion per day if intermittent renewable energy sources are being used. Highly durable electrolyzers can withstand the fluctuations in load associated with the use of intermittent energy sources and increase the lifetime before replacement. If the precious metal electrocatalysts can help to mitigate these challenges, the advantages in LCOH outweigh the higher initial capital invest by far.

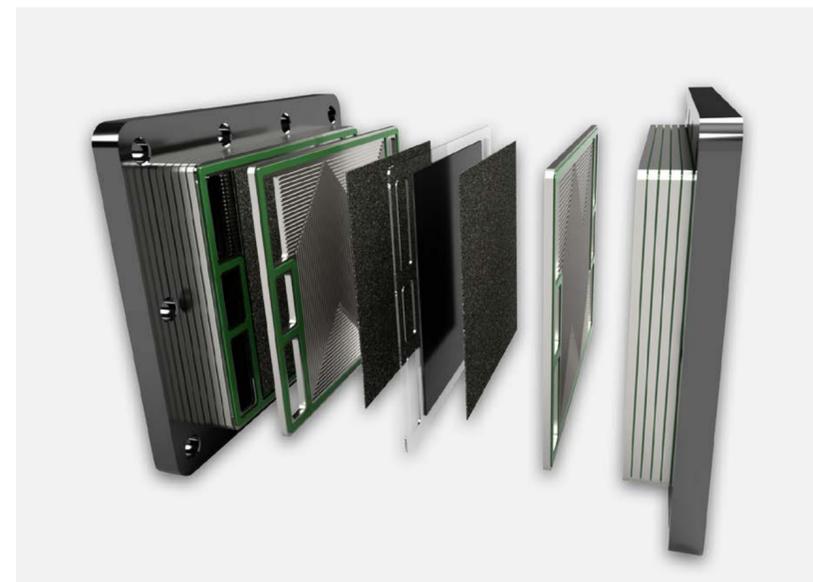
The tornado plot in **figure 9** shows the relative effects on LCOH through changes in:

- electricity prices,
- efficiency, i.e., power used to produce a kg of hydrogen,
- turndown ratio, i.e., the lowest possible current density at which an electrolyzer can be operated before it needs to be switched off to avoid operational failures⁶
- lifetime
- iridium loading

Efficiency, turndown ratio, and lifetime all benefit from the use of iridium catalysts or even from higher iridium loadings, though no generally valid correlation factor can be given independent from individual system designs. On the other hand, the changes to LCOH by higher or lower iridium content are comparatively low.

Even though iridium cost in legacy systems can make up 2% of the systems costs there is a net positive influence on total cost of ownership (in this case LCOH) of the electrolyzer which by far outweighs the cost of the raw materials.

Innovation in electrocatalyst development thus does not seek to replace iridium at the price of lower performance or durability. Innovation in catalyst development is to find the material with the best physio-chemical properties – which is iridium for PEMWE – and work on thrifting, i.e., the reduction of raw material content while preserving or even improving the properties of the system.



Commercial considerations for using PGMs in PEM fuel cells

The commercial use of fuel cells follows similar considerations as the commercial use of electrolyzers in that the operational costs over the system's lifetime are key. For the example of heavy-duty vehicles (HDV) or long-haul trucks those lifetime cost are calculated as the total cost of ownership (TCO) including the initial price of the vehicle, fuel costs, maintenance, insurance, road toll, taxes etc. Currently, the production costs for a fuel cell electric heavy-duty vehicle are considerably higher than for a comparable diesel-powered vehicle. However, the high price of dispensed hydrogen has a disproportionately large influence on the total cost of ownership (TCO) compared to traditional fuels.

The use of platinum in PEM fuel cells enables them to run at high durability and efficiency at the variable loads needed in a vehicle. As reduction of Pt contents in PEMFCs might come with a durability penalty, faster loss of efficiency or a restriction on the flexibility of operation conditions the development targets by governmental agencies like the DOE in the USA or the SRIA roadmap of the European Union's hydrogen programs allow for much higher Pt contents in HDV applications than for comparable passenger vehicles, for which the consumer market is more sensitive to acquisition costs than to TCO.

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⁶ The actual values of the turndown ratio depend on the manufacturer, but as a rule of thumb, the turndown ratios of commercial equipment decline in the order: PGM free AWE (ca. 15-20%), PGM-containing AWE (ca. 10-15%) and PGM-containing PEMWE (ca. 2.5-10%).

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The influence of hydrogen price at the gas station, efficiency in terms of kg hydrogen consumed per 100 km, fuel cell system costs and the different platinum loadings on TCO are shown in **figure 10**.

With efficiency and lifetime being positively affected by the use of Pt and their much larger influence on TCO than the changes in Pt-loading, it becomes clear why Pt reduction to the levels possible in passenger vehicles, or the level currently used in exhaust catalysts for diesel vehicles is not the highest priority for cost competitive deployment of fuel cell electric vehicles. Novel catalysts with lower loadings are being developed and industrialized, but again thrifiting of precious metals will not come at the price of reduced performance and durability. The largest hurdles for the deployment of hydrogen powered long haul trucks are the high hydrogen prices at the refilling stations.

These examples illustrate that Platinum Group Metals are used mainly to improve the commercial viability through increased efficiency. The selection of technologies for commercial operation is always done based on the use case and with a strong focus on efficiency and long-term stability. With that focus it not only makes sense to use Platinum Group Metals technologies, it would be outright counterproductive to skip their usage.



Figure 10. A comparison how changes to hydrogen price, hydrogen consumption, cost of the fuel cell system and platinum loading affect the total cost of ownership for a fuel cell powered long haul truck with a 300 kW fuel cell system. Data is based on the ICCT analysis for the 2030 fuel cell truck by H. Basma et. al.⁷ The influence of the Pt-loading was added assuming a Pt price of 40 \$/g and loading cases corresponding to passenger vehicles, state-of-the-art HDV loadings and the 2016 DOE loading target for HDV.

Chapter 3

Platinum Group Metals (PGMs) are by used in wide range of industries and applications.

The Hydrogen sector only presents a small part of the current yearly demand.

Since decades, mature industries satisfy a large part of their yearly gross demand through closed-loop recycling.

Precious metal trading is used to fill the remaining net demand.

Supply with Platinum Group Metals for hydrogen applications is not a new topic for the industry. In fact, use of the Platinum Group Metals is not limited to a single application or industry and the material supply chains are already mature and run at large volumes. This is in stark contrast to other green energy technologies, e.g., batteries or solar, were critical raw material supply chains needed to be build-up from scratch for specific new technologies.

A stable supply with PGMs is at the core of the technical and economic viability of many mature industrial sectors. Those industries successfully rely on established fully integrated precious metals houses which offer the three pillars of a sustainable PGM supply chain:

- 1) PGM trading to secure the necessary amounts,
- 2) product and technology development, and
- 3) recycling as part of the mature circular economy in the PGM sector.

As the hydrogen sector ramps up production capacities the increasing precious metal demands are met by an existing supply infrastructure. To appreciate how the precious metals industry can react to the advent of a new major use case, an understanding of the current supply and demand situation of Platinum Group Metals is important.

Origin and primary supply of Platinum Group Metals.

It is necessary to recognize that geological restrictions apply to the supply of individual Platinum Group Metals. As most Platinum Group Metals occur in orebodies alongside each other there can be no mining for a specific metal without considering the other materials. **Figure 11** shows the average ratio of the six commercially relevant precious metals in the mined orebodies of South Africa, the so-called 6E basket. Platinum and palladium make up the majority of the composition of the orebodies, followed by the more rare rhodium, ruthenium and iridium.

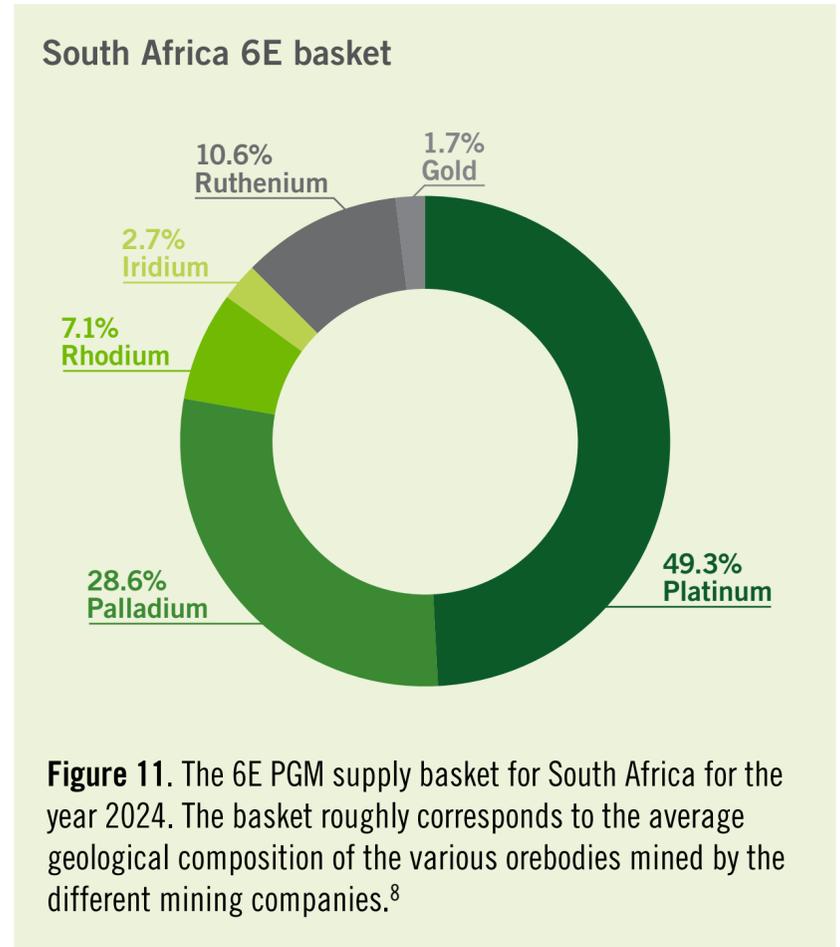


Figure 11. The 6E PGM supply basket for South Africa for the year 2024. The basket roughly corresponds to the average geological composition of the various orebodies mined by the different mining companies.⁸

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During precious metals refining, fine and precious metals present in the ores are separated via a set of highly specialized chemical processes (**figure 12**). In this multistep process, some steps are done directly by the mining operation and the final refining into a useable end-product is covered by precious metal houses. Precious metals houses like Heraeus Precious Metals are accredited by the London Bullion Association (LMB) which defines good deliverance

standards, oversees the global over-the-counter market for precious metals and provides the guidelines to ensure that precious metals are sourced responsible – addressing issues like money laundering and human rights abuses. In that way the precious metals houses ensure high quality and compliance standards value chain – from refining and trading over precious metals products to recycling.

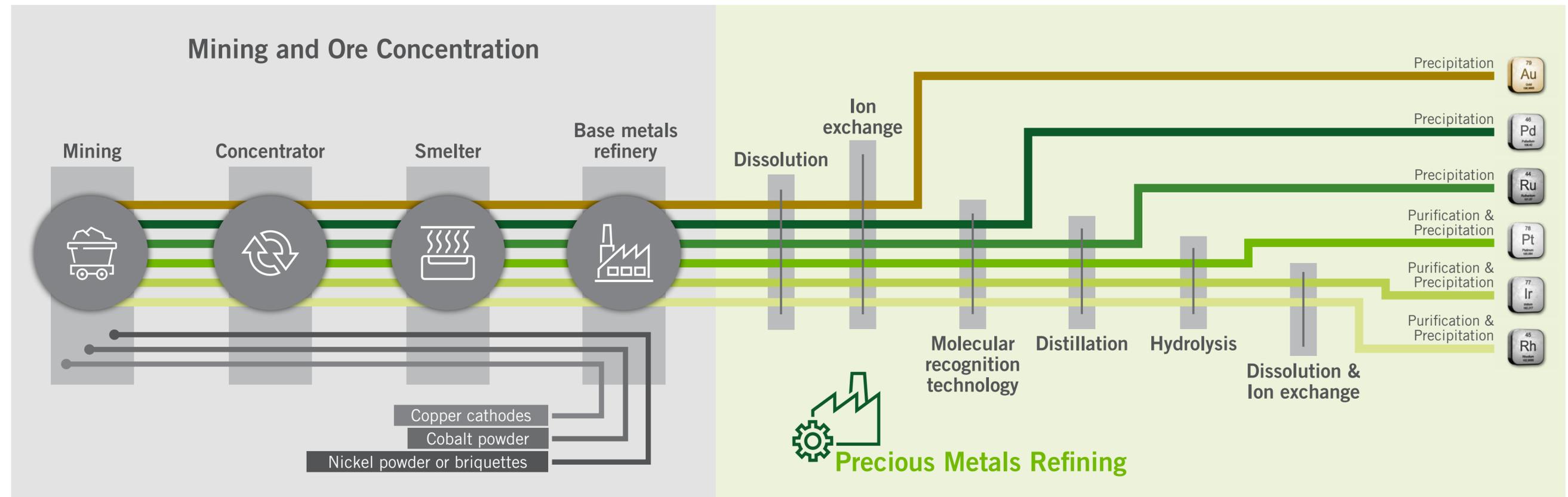


Figure 12. The role of mining and refining operations in the production of industrial grade PGM. The mines, mine, mill and concentrate the ore, base metal refineries take out copper, nickel and cobalt. The precious metal rich concentrate is than further concentrated and individually refined for gold and the PGMs going through a multistep process. For comparison the typical duration to recover the Pt from mining is 6-8 weeks, for Pd 8-9 weeks, and for Ir 12-15 weeks. Source: Impala Platinum.

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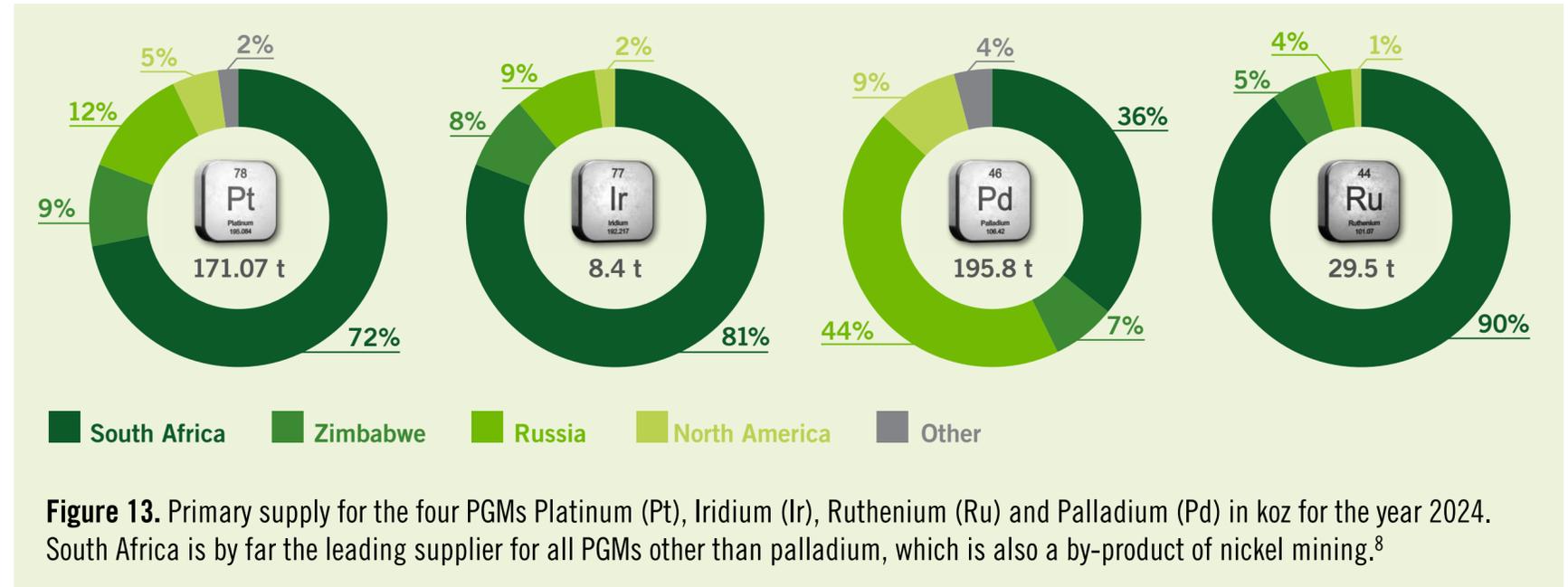
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South African deposits alone represent more than 70% of the worlds known platinum resources and both the largest and second largest PGM deposits are located respectively in northeast South Africa and in neighboring Zimbabwe. The south African countries therefore dominate the supply of Platinum Group Metals with only smaller contributions to the world market from mines in the United States, Canada, and Russia. (see figure 13). Only palladium can be sourced at significant amounts from outside of southern Africa, as it also occurs in association with Nickel and Copper sulfide deposits and is thus mined as a valuable by-product of some Nickel mining operations.

Overall the mined amounts of different Platinum Group Metals are, however, tightly linked which can limit the flexibility of supply for an individual Platinum Group Metal with their highly specific and individual industrial use and demand. For the hydrogen industry this means that the amount of iridium sourced through mining cannot simply be increased with increasing demand. The available iridium from mining operations only increases if the demand for



the leading materials platinum and palladium increases, as well. An important part of the business model at precious metal houses is to support such challenges and ensure an efficient distribution of the various PGMs into different new and established industrial applications. Efficient sourcing, trading but also product development and innovation for metal thriving solutions plays a crucial role to balance illiquid markets.

Chapter 3

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Demand for Platinum Group Metals and industrial use.

The largest overall users of Platinum Group Metals are the chemical, automotive and electronics industry. The PGM industry distinguishes between gross and net demand of those industries (see figure 14). Gross demand is the total yearly amount manufactured into products and net demand is the amount that an industry needs to source from the markets to do so. This is an important distinction as a large share of PGMs are part of a truly circular economy in which the same company reuses the raw materials end-of-life through closed-loop recycling. Mature industries can often satisfy a significant part of their demand through closed-loop recycling.

The net demand is sourced from the markets, which trade material sourced as newly mined and from open-loop recycling. In open-loop recycling, recycled metals are sold back to the market, as they often come from consumer products that have been collected by recycling companies for the purpose of turning a profit through PGM sales.



Platinum Group Metal Trading

Platinum and palladium are traded at the commodity markets, while the less abundant metals iridium and ruthenium are traded on an over-the-counter basis. Heraeus Precious Metals and SFA Oxford provided insights and transparency into the development of precious metal demands, prices and the reasons for fluctuations in price, demand and supply through its yearly publications “The Platinum Standard”⁹ and the “The Palladium Standard”¹⁰.

9 Heraeus Precious Metals GmbH & Co. KG (2025) <https://www.heraeus-precious-metals.com/de/precious-metal-prices-reports/the-platinum-standard/>

10 Heraeus Precious Metals GmbH & Co. KG (2025) <https://www.heraeus-precious-metals.com/de/precious-metal-prices-reports/the-palladium-standard/>

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Net demand from various industries

The net demand for platinum (Pt), iridium (Ir), ruthenium (Ru) and palladium (Pd) from different industries is shown in **figure 15**. A comparison of the share the hydrogen economy of the current overall demand for the individual PGMs is shown in more detail in **figure 16**. Especially for platinum and palladium the demand of the hydrogen sector is currently rather small in comparison to other industries with a share of less than 1% in 2024.

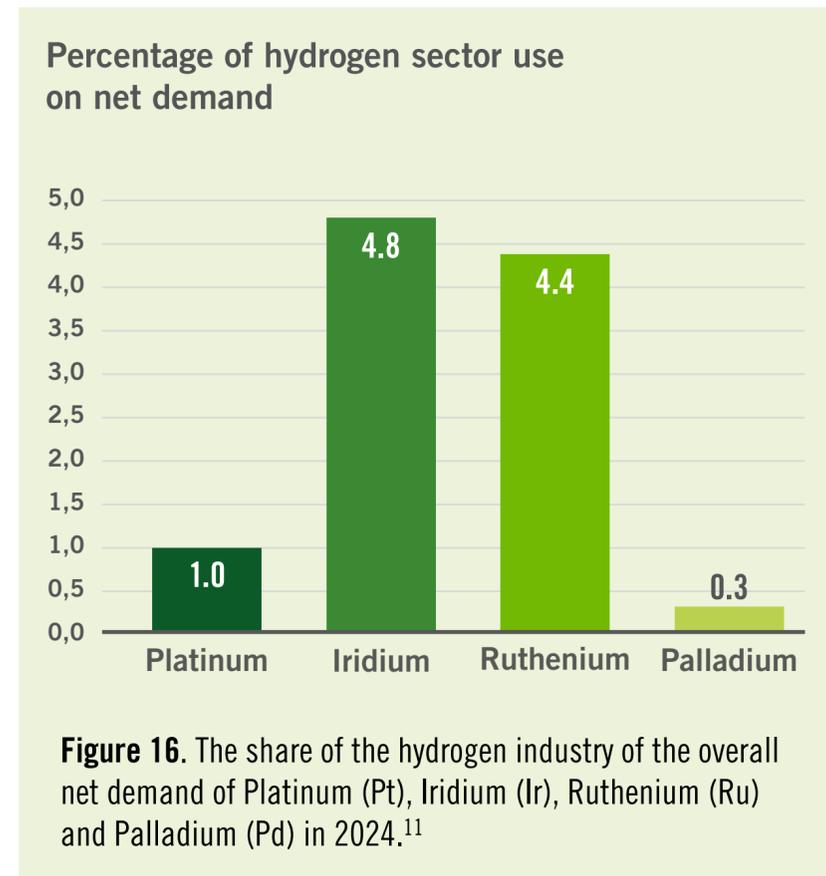


Figure 16. The share of the hydrogen industry of the overall net demand of Platinum (Pt), Iridium (Ir), Ruthenium (Ru) and Palladium (Pd) in 2024.¹¹

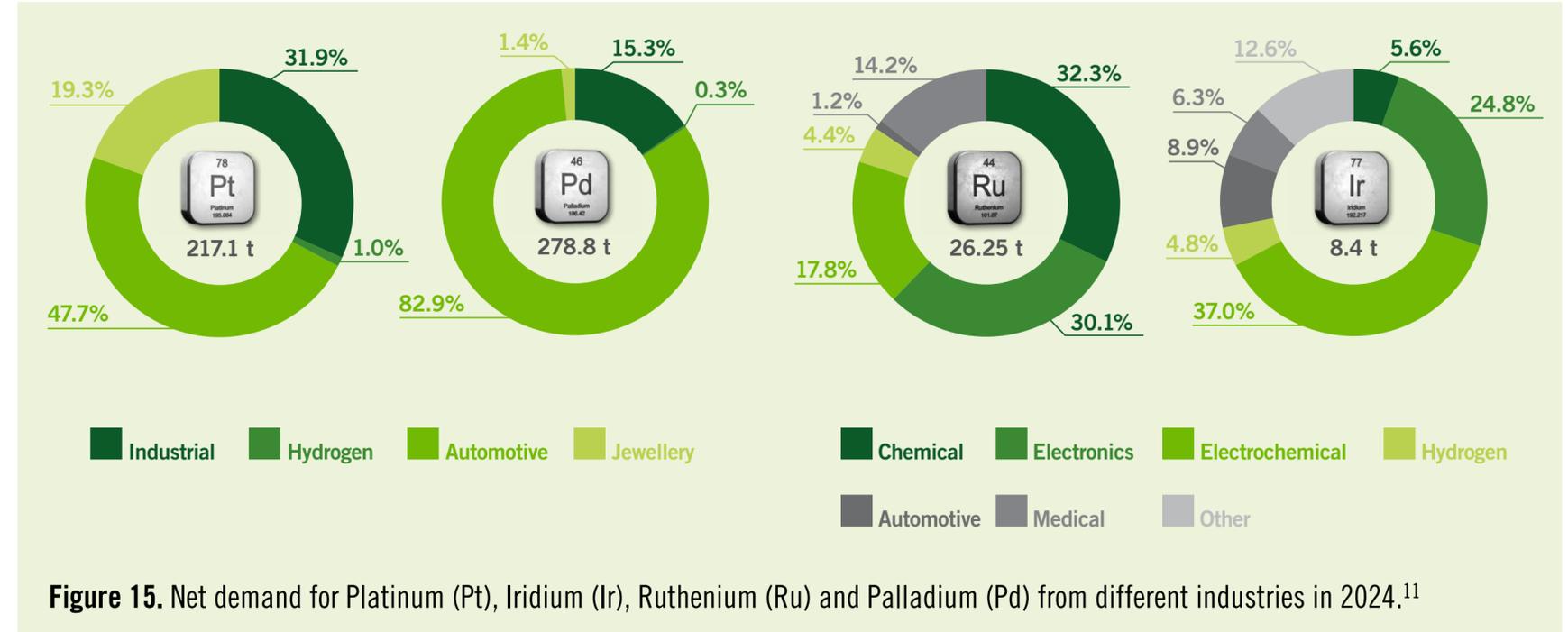


Figure 15. Net demand for Platinum (Pt), Iridium (Ir), Ruthenium (Ru) and Palladium (Pd) from different industries in 2024.¹¹

Those two materials are also the most abundant PGMs and unlike other PGMs platinum and palladium are traded on the public markets with high liquidity.

For ruthenium and especially for iridium the share of the overall demand in 2024 was already around 5%. At such values the emerging hydrogen sector does not present an issue today. The situation can, however, be more tense for the future, if demand further increases as expected.

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Challenges to the markets by the growing hydrogen industry

It is evident that the increasing demand from the hydrogen sector meets a group of materials with different available amounts, different demand from different legacy industries and different trading structures. Despite the materials being linked through geology and joint mining operations, a resilient build-up of the hydrogen sector presents individual challenges for the individual Platinum Group Metals. A one size fits all approach in regulation or support will not work.

The material for which increasing demand from the hydrogen industry is most consequential is iridium. Within the ramp-up of production capacities for electrolyzers the iridium supply for the hydrogen industry needs to be managed. Already existing low-loading catalyst technologies allow for iridium thrifting, but have not been prioritized in the last couple of years for installed systems, considering the low impact of reduced iridium loadings on the LCOH (see above).

Based on the same commercial considerations the increasing iridium demand will not stop the hydrogen scale-up on a short or intermediate timescale. Potential price increases for iridium as a consequence of increasing demand at tight supply can, in fact, best be absorbed by the hydrogen industry.

However, the increased iridium demand can severely disrupt other industries. Especially the medical industry is in a less fortunate position, as it cannot recycle its raw material and is sensitive to price increases, that might make certain medical applications no longer feasible.

Managing the iridium supply and demand is a challenge that affect all industries not only the hydrogen industry. Thrifting of iridium in the hydrogen economy protect the viability of other industries.





Conclusion

Conclusion

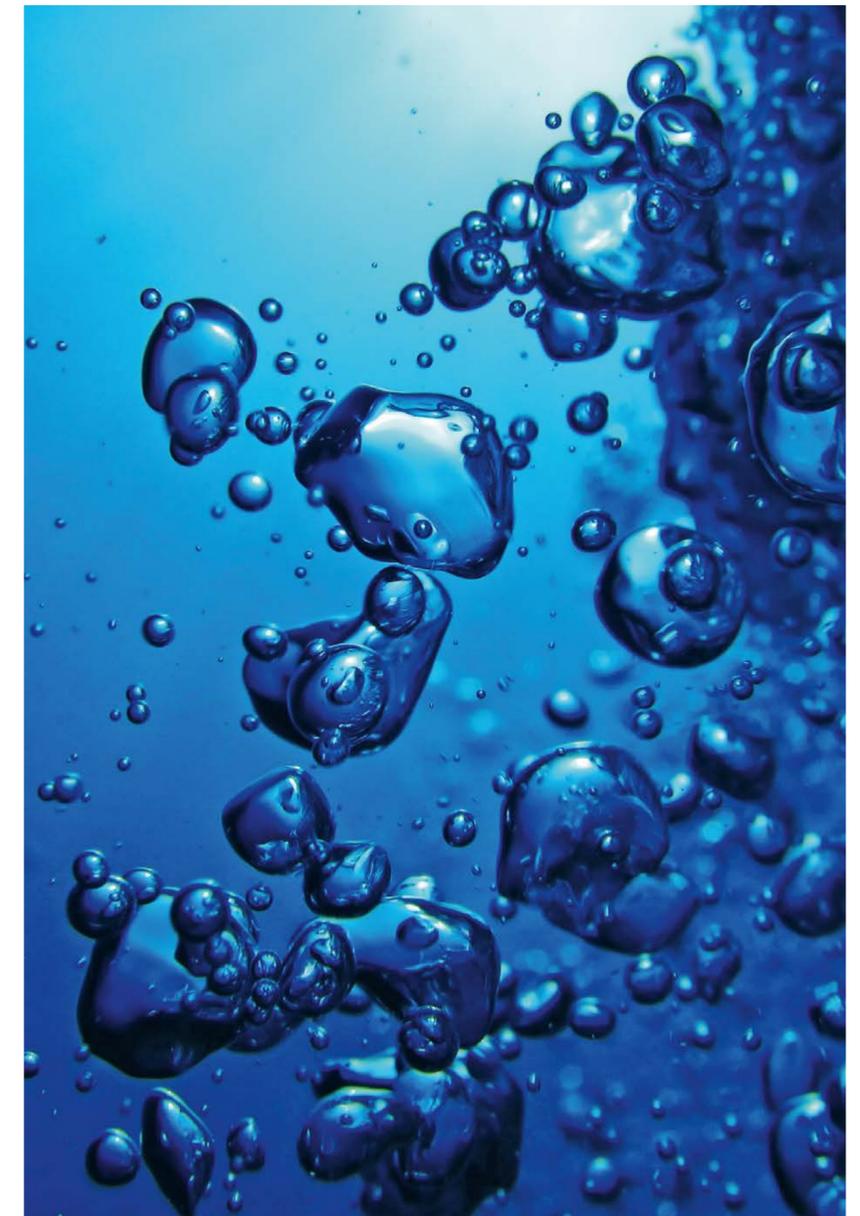
The use of Platinum Group Metals (PGMs) in the hydrogen industry is almost universal and the precious metal industry is ready to supply the ongoing ramp-up of the hydrogen economy. Platinum Group Metals are used in many technologies and along the complete chain of production, transport and use of green hydrogen. Resilience in equipment manufacturing for green hydrogen therefore does not mean to forgo individual technologies like PEM water electrolysis. Resilience for the hydrogen economy means to provide hydrogen in the most efficient way possible and to profit from the existing competitive raw material supply chains without disturbing the supply for other industries.

What are the recommendations for the different players?

- **Engineering, Procurement Construction (EPC) companies and hydrogen producers** should solely focus on the efficiency of their facilities and levelized cost of hydrogen to build up a cost competitive green hydrogen supply.
- **Producers of hydrogen equipment** have invested heavily in the scale-up of production capacities. Their next step is strategic: in order to stay relevant and secure future scale-up now, next generation technologies need to be considered that combine thrifting of iridium with better performance.

- **Users of green hydrogen**, in commercial fuel cell applications as well as in the chemical industry have shown the technological feasibilities. With more stable business cases they now should strategically focus on increasing the efficiency of their application to decrease costs over lifetime.
- **The precious metals industry** needs to take care of the resilience in supply of Platinum Group Metals through trading and product innovation, and this means stability in supply and demand of all collectively mined Platinum Group Metals. All industries that use Platinum Group Metals need to be considered to provide a resilient supply supported by a diversified demand.
- **Policy makers** need to do both – do the thing with the most positive regulatory impact and avoid harmful actions: There is no need for a policy that seeks to dictate which technologies should be used for which application. This question should be decided by technical and economical efficiency. Also policy should not try to define the next generation of materials used in hydrogen technologies, as those material already exist. Instead, stable pricing and clear pricing schemes for green hydrogen should enable investments in green hydrogen production and applications that also drive development and investment along the supply chain. Policy should enable manufactures

to showcase the advantages and reliability of next generation technologies by supporting large scale demonstrator projects and thus help to build trust in technological advances.





About Heraeus

Heraeus is a globally active, family-owned technology group. Based in Hanau, Germany, the company comprises 15 operating companies whose products and services span the Business Areas of Metals & Recycling, Healthcare, Semiconductor & Electronics, and Industrials. In fiscal year 2024, Heraeus generated revenues of €29.4 billion and employed roughly 15,200 people across 40 countries. This makes Heraeus one of the top ten largest family-owned enterprises in Germany.

With deep expertise in advanced materials, Heraeus is a leader across key global industries. The group ranks among the foremost providers of precious metals, supplies quartz glass for the semiconductor and telecommunications sectors, and manufactures sensors for the steel industry. In addition, its materials and technologies for medical technology help improve the quality of life for millions of people worldwide.

Innovation is the central driver of Heraeus's success. Each year, six percent of revenues (based on revenues excluding precious metals) are reinvested into research and development. Beyond that, the company partners with leading research and educational institutions around the world.

About Heraeus Precious Metals

Heraeus Precious Metals is globally leading in the precious metals industry. The company is part of the Heraeus Group and covers the value chain from trading to precious metals products to refining and recycling. It has extensive expertise in all Platinum Group Metals as well as gold and silver.

With more than 3,000 employees at 16 sites worldwide, Heraeus Precious Metals offers a broad portfolio of products that are essential for many industries such as the automotive, chemicals, semiconductor, pharmaceutical, hydrogen and jewelry industry.

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